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RESEARCH DEPARTMENT

A CONTINUOUSLY VARIABLE DELAY LINE FOR TELEVISION SIGNALS

Report No. T-085

(1962/16)

THE BRITISH BROADCASTING CORPORATION
ENGINEERING DIVISION

RESEARCH DEPARTMENT

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May 1962

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SUMMARY

The construction and characteristics of an ultrasonic delay line using mercury as the transmission medium are discussed in some detail, and an experimental variable delay unit suitable for a 405-line television system is described. The report gives an account of the defects of the line and the difficulties encountered in constructing the video delay unit; some indication is given as to the possibility of extending the use of the line to television systems using a higher line frequency.

1. INTRODUCTION

There are many applications in the field of television for devices capable of delaying a picture by one or more television-line periods, and ultrasonic delay lines, which were developed principally for use in computer and radar applications, have been successfully used for some of them.[1, 2, 3] Of the delay lines at present being manufactured, those useful for television purposes have either fused quartz or mercury as the transmission medium. Whilst fused quartz is a cheaper and more tractable material than mercury, and is slightly more suitable for delay line applications, a line having mercury as the transmission medium can have the great advantage of being made continuously variable over a range of 10:1. Such a line, made by Mullard Research Laboratories, was chosen for use in the video delay unit; it produces a delay which is continuously variable between 25 μs and 330 μs. For some applications, it is necessary to have a range of delay continuously variable from zero, and in order to be able to simulate this, a second mercury delay line, which has similar electrical characteristics to the variable line but a fixed delay preset to a value of 30 μs, is included. Fig. 1 shows a general view of the complete delay unit.

2. THE MECHANISM AND CONSTRUCTION OF MERCURY DELAY LINES

Essentially, a mercury delay line consists of a bath of mercury with an electro-mechanical transducer at each end. A suitable electrical signal applied to one of these transducers causes it to vibrate mechanically and so set up a longitudinal pressure-wave in the mercury. This is transmitted to the second transducer with a velocity of approximately 1·5 mm/μs, producing across it a voltage representative of the signal applied to the first transducer but delayed in time. A delay of one television-line period, for a 405-line system, can be achieved with a line length of 15 cm (6 in).

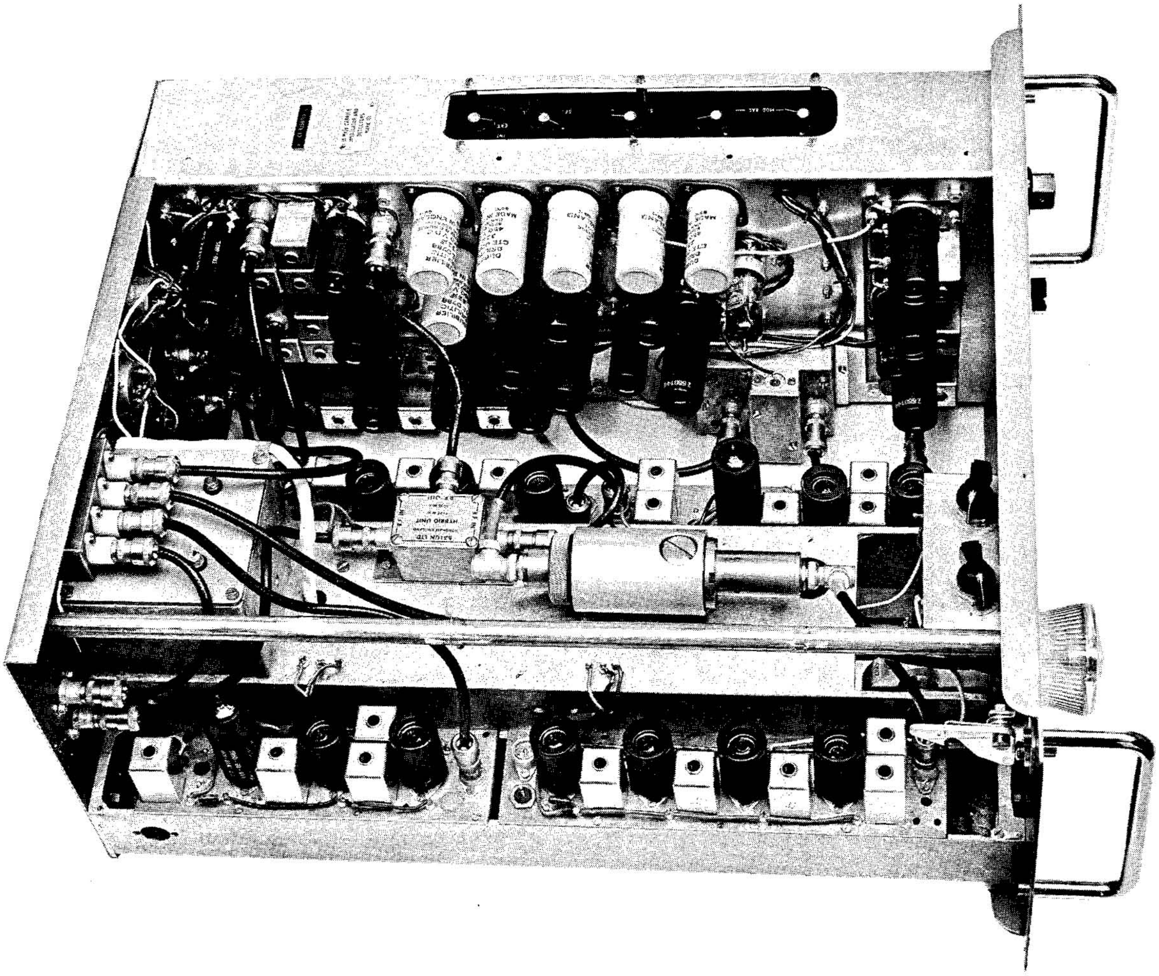

Fig. 1 - The video delay unit

The performance of a mercury delay line, especially with regard to bandwidth, insertion loss, and any secondary responses which may occur, is largely dependent upon three factors. These are:

a) the acoustical matching of the transducers to the transmission medium,
b) the efficiency with which the transducer converts electrical energy into mechanical energy and vice versa (usually termed the electro-mechanical coupling factor),
c) the electrical impedance presented to the external circuits by the transducers.

In order to obtain a large fractional bandwidth*, it is necessary for the transducers to be acoustically matched to the mercury. It is fortunate that quartz-crystal transducers approximately match mercury and may be designed to operate at frequencies up to at least 30 Mc/s, which makes bandwidths of the order of 10 Mc/s attainable.

*Fractional bandwidth = bandwidth/band-centre frequency

The transducer usually consists of an X-cut crystal driven so as to vibrate in the thickness mode; see Fig. 2. The electro-mechanical coupling of these crystals is exceedingly poor and introduces a large loss; this is the major contribution to the insertion loss of the line*. The loss due to transmission through the mercury is relatively small, being about 6 dB for a path length of 40 cm (16 in). The total insertion loss of the line depends to some extent upon the electrical network terminating it, but usually in excess of 50 dB at the band-centre frequency.

With such a high insertion loss it is important to try to ensure that all the signal launched into the mercury travels to the receiver along the chosen transmission path. In practice the diameter of the crystals used as transducers is 100 wavelengths of the centre frequency, giving rise to a radiation pattern of quite high directivity. The first null in the radiation pattern occurs at an angle of 40' to the normal, and the maximum of the first sidelobe is at 55' with an amplitude 18 dB less than that of the main lobe.[4]

The signal radiated through the sidelobes strikes the walls of the container, usually a steel tank, and, because of the roughness of the walls, the wave becomes scattered; only a minute proportion finds its way to the receiving transducer to produce an unwanted signal. A far more troublesome form of secondary response is caused by the poor electro-mechanical coupling of each transducer; the mechanical energy not transformed into electrical energy by the receiving transducer must be re-radiated and, although a large proportion of this can be absorbed by an acoustical termination on the side of the crystal remote from the mercury, some

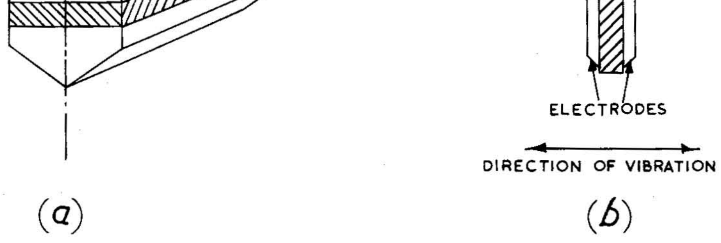

Fig. 2 - (a) Diagram of a section of a quartz crystal showing an X-cut
(b) An X-cut crystal operating in the thickness mode

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*Defined as, Insertion loss = 20 $\log_{10}$ Input Voltage/Output Voltage, dB.

must be re-radiated back along its original path. This energy will eventually reach the sending transducer where, after a second reflection, it will traverse the delaying medium for the third time to produce an unwanted "third-time-round" response. This effect can be largely eliminated by tilting the receiver transducer so that the "third-time-round" signal is incident at the angle of the first null in the radiation pattern. The angle of incidence of the main signal will then be equal to one third of the "null" angle, which will increase the insertion loss by only 1·8 dB.[4] By the use of this artifice, and careful design of the acoustical terminations of the line, the amplitude of the spurious responses can be restricted to at least 40 dB below that of the wanted signal.

The form of the attenuation/frequency characteristic of the line depends upon many factors. The centre frequency is largely determined by the transducers, the wavelength in quartz being approximately twice the crystal thickness. The bandwidth depends upon the centre frequency and is also affected by the load presented to each crystal by the transmission medium and the acoustical termination. In order to achieve maximum bandwidth, the acoustical termination can take the form of a mercury-filled cavity having a shape designed to trap and absorb the signal entering it. A simpler and more common method of termination is to provide each crystal with a lead backing. The form of the attenuation/frequency characteristic is also influenced by the orientation of the crystals. Owing to the fact that the radiation pattern of a crystal transducer varies with frequency, a change in the angle of incidence affects the attenuation/frequency characteristic of the line. When the receiver transducer is adjusted so as to suppress the "third-time-round" signal, the insertion loss at high frequencies is increased. Finally, as the attenuation of the acoustic wave is proportional to the square of the frequency, the transmission of the signal through the mercury has a very definite effect on the characteristic; this factor places an upper limit on the frequency which can be used with a given length of line.

The third factor determining the performance of the line is the electrical impedance presented to the external circuits by the transducers. Equivalent circuits for crystal transducers have been developed and described in the literature.[4,5,6] In practice, the impedance seen across the terminals of a transducer reduces to a capacitance in parallel with a resistance, the latter however, is of such a high value that for all practical purposes it may be ignored.

The two forms of line incorporated in the delay unit are described below.

2.1 Adjustable Line Type 4014

This is a simple type of line consisting of a nickel-plated mild-steel tank with a lead-backed quartz-crystal transducer suitably mounted at each end. The transmitting transducer may be moved axially over a short distance, thus providing a delay adjustment. The receiving transducer can be tilted to reduce the spurious responses. The attenuation/frequency characteristic of this line is shown in Fig. 3.

2.2 Continuously-Variable Line Type 4016

The continuously-variable line has a delay range of approximately 11:1. This is obtained by varying the path length of the acoustical wave as follows: both transducers are mounted at the same end of a rectangular mild-steel tank. The wave

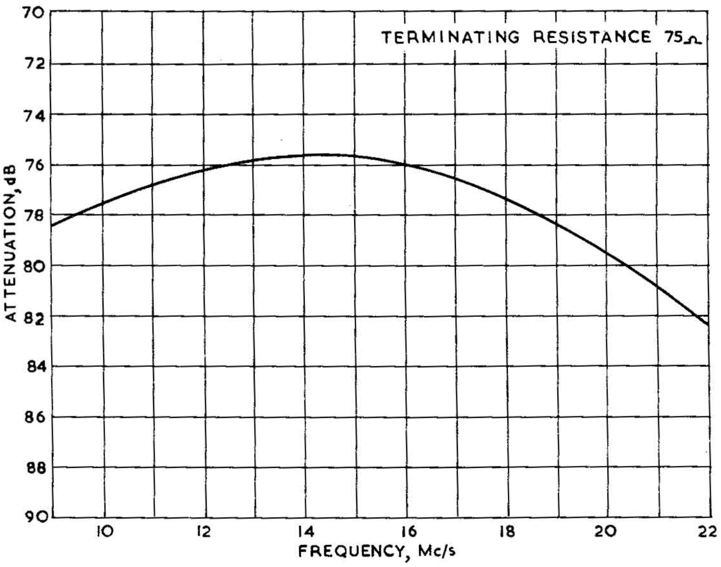

Fig. 3 - The attenuation/frequency characteristic of the adjustable mercury delay line type MS4014

radiated from the transmitting transducer enters a movable corner reflector, from which the signal is returned to the receiving transducer. The corner reflector is mounted on a steel lead-screw having a pitch such that one complete turn changes the delay by 10 μs. The attenuation/frequency characteristic of this line changes with delay and is shown in Fig. 4 for the maximum and minimum delay settings.

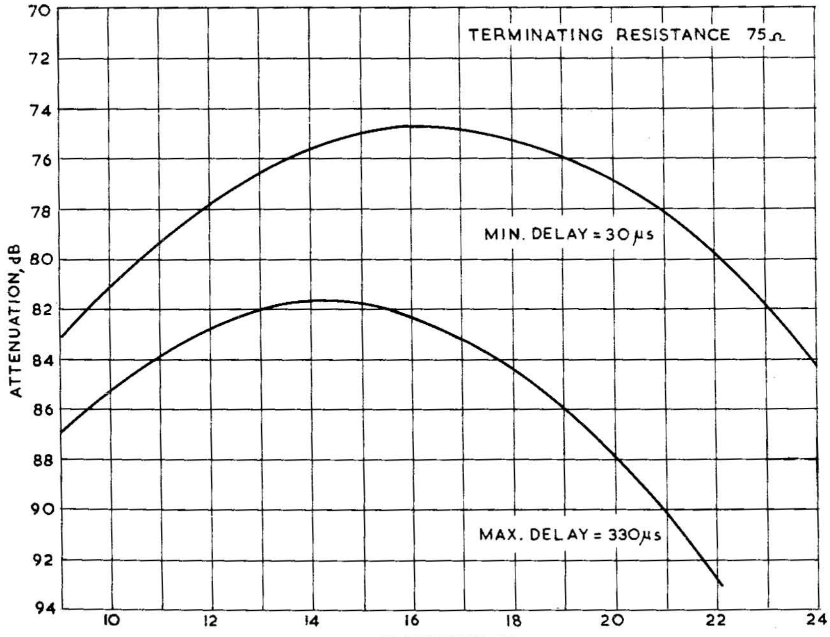

Fig. 4 - The attenuation/frequency characteristics of the continuously variable mercury delay line type MS4016

3. DESCRIPTION OF THE VIDEO DELAY UNIT

3.1. General Description

The video delay unit shown in Fig. 1 consists of two separate delaying channels both driven from the same signal source. One channel uses the adjustable line to produce an output delayed by 30 μs; the other channel uses the continuously-variable line to produce an output whose delay may be adjusted between 25 μs and 330 μs. Thus the second output can be delayed from -5 μs to +300 μs with respect to the first. The electrical characteristics of the lines are sufficiently similar for the design of the two channels to be identical, and the bandwidth available will accommodate, using a 15 Mc/s carrier, the amplitude-modulated double-sideband transmission of a 405-line television picture.

The block diagram of the complete unit is shown in Fig. 5; the sub-divisions indicate the three sub-units of which it is constructed. The video signal is modulated on a locally-generated carrier and the resulting signal is amplified and split into three separate outputs. Two of these outputs are used to drive the principal delaying channels, each of which consists of an input amplifier, a mercury delay line, and an output amplifier. The third output is delayed, attenuated, and added back to the output of the continuously-variable channel, in order to cancel out some direct crosstalk which occurs between the transducers. The amplitude of this crosstalk, which occurs inside the line as a result of its construction, is approximately 40 dB below that of the wanted signal; the use of the cancelling circuit reduces the crosstalk by a further 20 dB. Crosstalk is also liable to occur outside the line because of coupling between the networks connecting the transducers to the amplifiers. This has been reduced to negligible proportions by thick copper screens and the careful choice of earth connections. The delayed signals from the output amplifiers are detected by means of germanium diodes and fed through cathode followers to the output terminals.

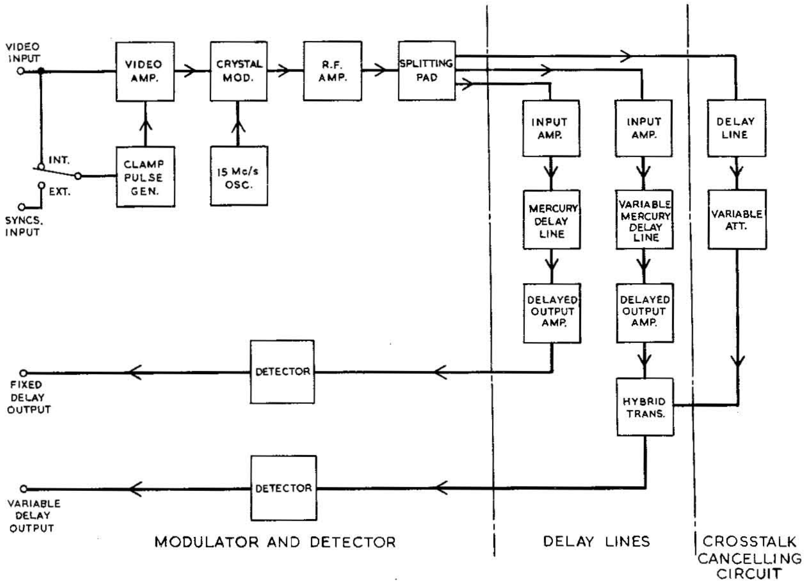

Fig. 5 - Block diagram of the video delay unit

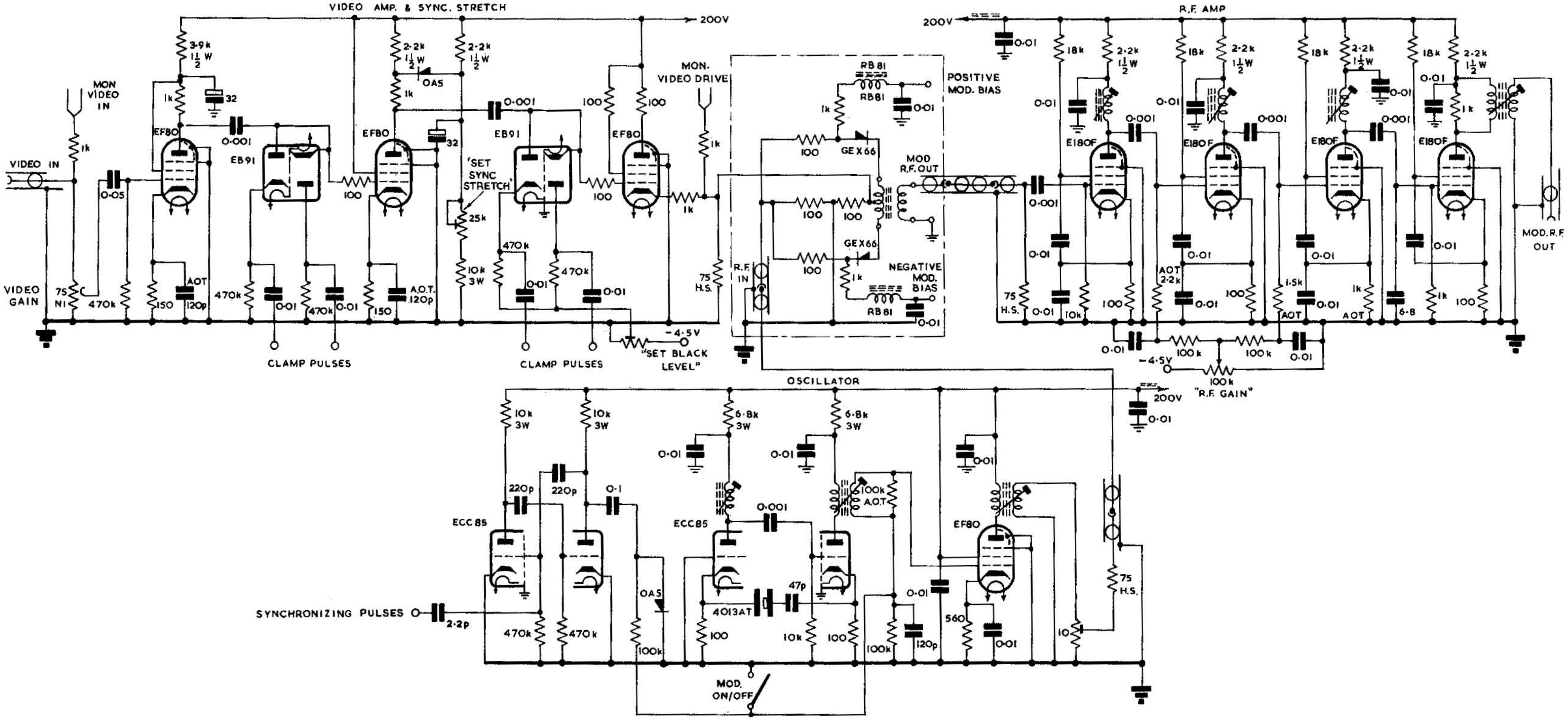

Fig. 6 - Circuit diagram of the modulator

3.2 Generation of the Modulated Signal

Fig. 6 is a diagram of the circuits used to produce the modulated signal. A "clamped" video amplifier of conventional design is used to drive a crystal modulator. The 15 Mc/s carrier is generated by a crystal-controlled oscillator and fed to the modulator through a buffer amplifier. In order to facilitate adjustment of the modulator, the carrier can be 100% modulated by a 2·5 kc/s square wave locked to the television line-synchronizing pulses. The signal from the modulator is raised in level by an amplifier similar in design to that described in Section 3.4 of this report.

3.3 Input Amplifier

The circuit diagram of the input amplifier is shown in Fig. 7; it consists of a buffer amplifier, which permits the input line to be correctly terminated, followed by two further stages incorporating negative feedback. In order to obtain a high signal-to-noise ratio the input transducer must be driven with as large a signal as possible. For this reason, the output valve must handle large current swings, and use is made of negative feedback in order to reduce the non-linear distortion which would otherwise result.

The network coupling the anode of the output valve to the transducer fulfils two purposes: it transforms the signal current from the output valve into a suitable voltage across the transducer, and at the same time is used to correct the attenuation/frequency characteristic of the mercury delay line.

The design of this network was complicated by the fact that the characteristic of the variable line changes in centre frequency and bandwidth as the delay is varied (see Fig. 4). It was decided to equalize the line for the mid-setting of delay; the resulting overall attenuation/frequency characteristics at maximum and minimum delay are shown in Fig. 8. These characteristics have an approximately constant slope of 0·3 dB per Mc/s within the passband, but this will have negligible effect on a television waveform if a double-sideband amplitude modulator is used together with an envelope detector. The attenuation/frequency characteristic of the line at the mid-setting of delay is shown in Fig. 9. In order to design an equalizer for the line, it is convenient to transform the bandpass response into an equivalent low-pass response and find a simple expression to represent this. A suitable expression is given by

$$|A\ (f)| = [1 + 0{\cdot}94\ (f/10)^2 + 1{\cdot}36\ (f/10)^4]^{\frac{1}{2}*},$$

where $A\ (f)$ is the complex attenuation of the line and f is the equivalent low-pass frequency (Mc/s).

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* For the purposes of calculation, this expression is most conveniently stated in terms of megacycles divided by ten ($f/10$).

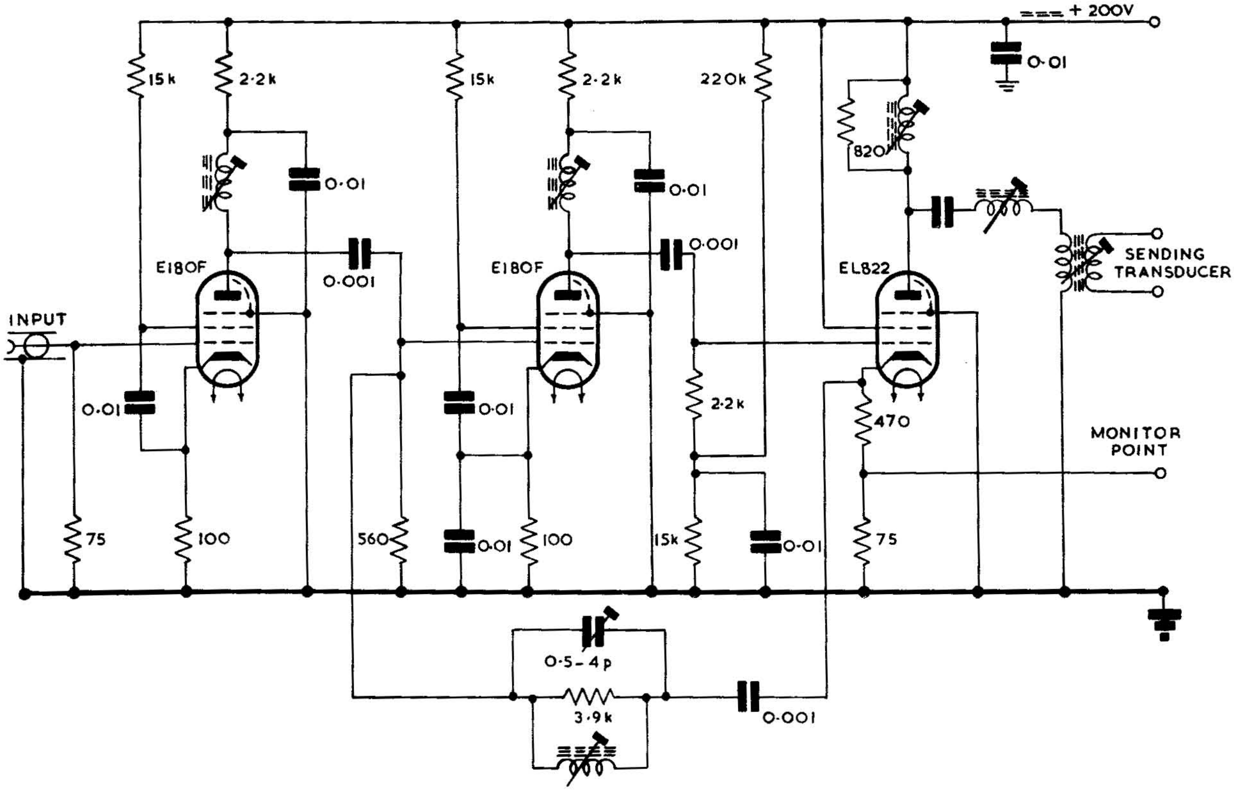


Fig. 7 - Circuit diagram of the input amplifier

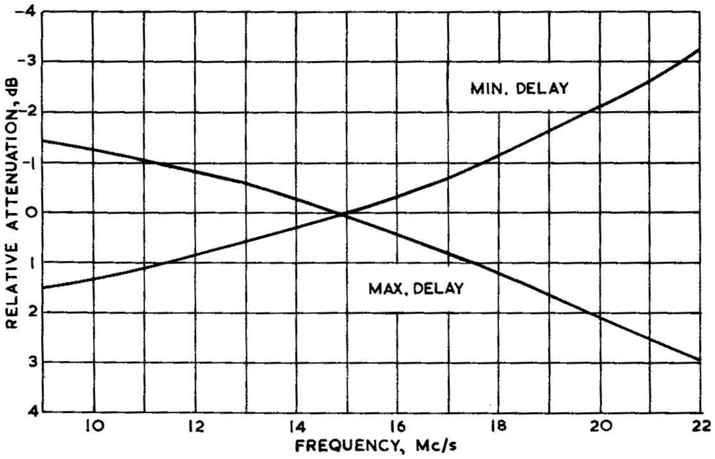


Fig. 8 - Attenuation/frequency characteristics of the continuously variable line when equalized for the mid-setting of delay

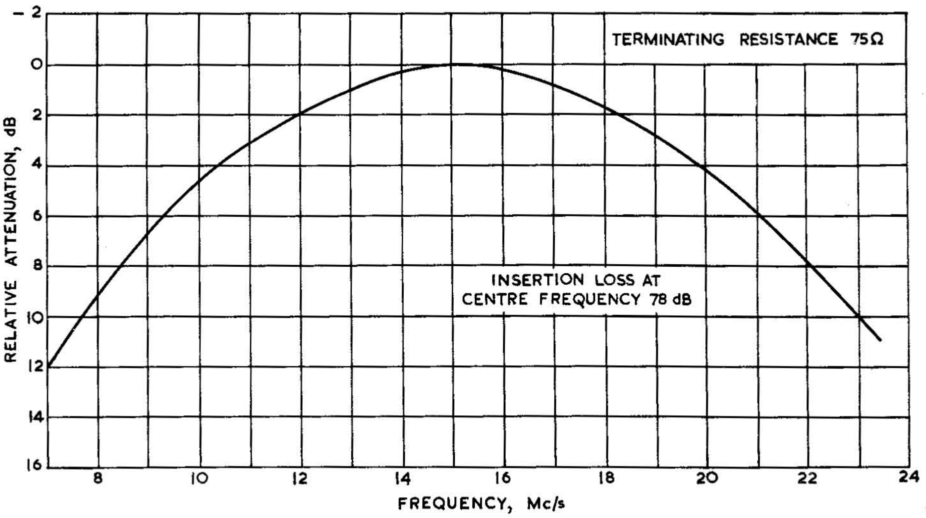
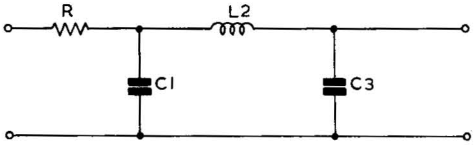


Fig. 9 - The attenuation/frequency characteristic of the continuously variable line at mid-setting of delay

The simplest form of low-pass circuit which can be used as a coupling network in these circumstances is a π-section as shown in Fig. 10. The attenuation of this network is of the form

$$|B\ (f)| = [1 + b_1\ (f/10)^2 + b_2\ (f/10)^4 + b_3\ (f/10)^6]^{\frac{1}{2}}.$$

Fig. 10 - Circuit diagram of the low-pass equalising section



By multiplying together $|A\ (f)|$ and $|B\ (f)|$ and reducing the appropriate coefficients to zero, a fourth-order maximally-flat function is obtained. This process results in a set of equations relating the coefficients of $|B\ (f)|$ with those of $|A\ (f)|$. Thus b_1, b_2 and b_3 may be determined, hence we obtain the expression

$$|B\ (f)| = [1 + 0{\cdot}94\ (f/10)^2 - 0{\cdot}48\ (f/10)^4 + 1{\cdot}73\ (f/10)^6]^{\frac{1}{2}}.$$

By comparing this expression with the transfer function of the low-pass network, equations may be derived relating the network parameters to b_1, b_2 and b_3. These equations may be used to determine the circuit component values in terms of the capacitance presented by the output valve.

The low-pass network can now be transformed into the bandpass network of Fig. 11. The transformer T1 is necessary in order to transform the transducer capacitance to a value suitable for inclusion in the coupling network; the transformer need not be perfect, for any leakage inductance can be compensated by adjustment of the series inductance L2. The characteristic of the bandpass network is shown in Fig. 12 and the combined characteristic of the coupling network and the line (at the mid-setting of delay) is shown in Fig. 13.

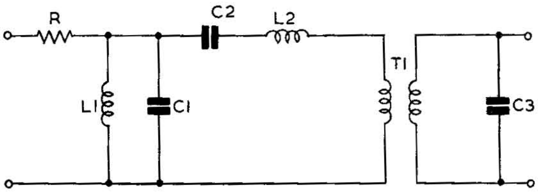


Fig. 11 - Circuit diagram of the band-pass equalizing section

3.4 Output Amplifier

The circuit of the output amplifier is shown in Fig. 14; it consists of a stagger-tuned triple followed by an output stage. The amplifier has a maximum gain of approximately 60 dB which can be reduced by adjusting the negative bias applied to the grids of the second and third valves. The output stage is designed to have unity gain and an output impedance of 75 Ω within the passband.

The signal-to-noise ratio of the video delay unit is largely determined by the noise contributed by the first valve of this amplifier, however, the amplitude of the input signal is sufficient to allow a pentode to be used.

3.5 Detector and Video Amplifier

The circuit of the detector and video amplifier is shown in Fig. 15. It consists of an amplifying stage coupled, by means of a bandpass filter, to a diode detector; the output of the detector is fed through a low-pass filter to a simple cathode-follower output stage. As the lowest sideband frequency of the modulated signal is only two octaves removed from the highest video frequency it is desirable that the low-pass filter have a rate of cut-off of at least 24 dB per octave; furthermore, the filter must not introduce any significant group-delay distortion within the video passband. These requirements are achieved by using a filter with a cut-off frequency of twice the highest video frequency and maximum attenuation at the carrier frequency; its design is described in the Appendix.

4. PERFORMANCE

The degradation of a video signal by the delay unit may be judged from the reproductions of Test Card "C" shown in Figs. 16, 17 and 18. Fig. 16 shows the input signal, whilst Figs. 17 and 18 show the signal delayed by 150 μs and 300 μs respectively. The residual crosstalk discussed in Section 3.1 can be observed in Fig. 17; it is more pronounced in Fig. 18 owing to the increased insertion loss of the line. The ratio of peak-to-peak video signal (excluding synchronizing pulses) to r.m.s. noise is dependent upon the delay setting. It varies from 38 dB at maximum delay to 44 dB at minimum delay.

Although the experimental unit described in this report was designed for a 405-line television system, the equalized delay line has sufficient bandwidth for a 625-line system if a single-sideband system of modulation is used.* In this case, the change of slope of the attenuation/frequency characteristic with delay could no

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*It may be possible to extend the use of the line to an 819-line system by means of a more complex equalizing network.

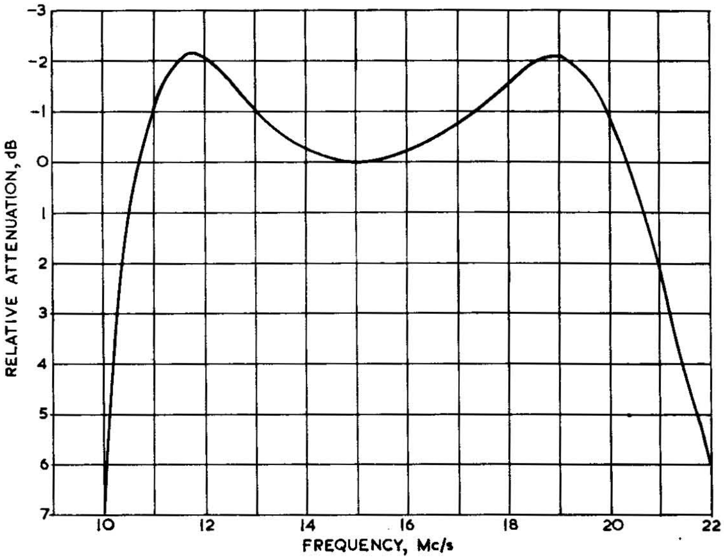

Fig. 12 - The attenuation/frequency characteristic of the band-pass equalizing section

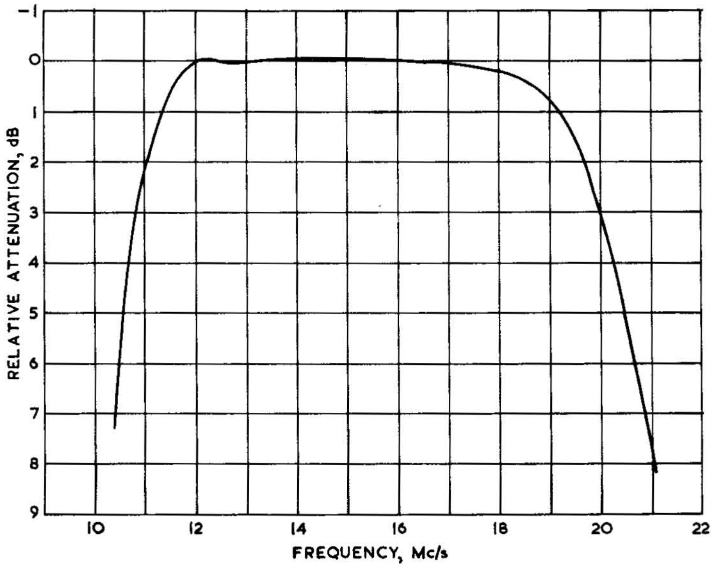

Fig. 13 - The attenuation/frequency characteristic of the equalized continuously variable line for the mid-setting of delay

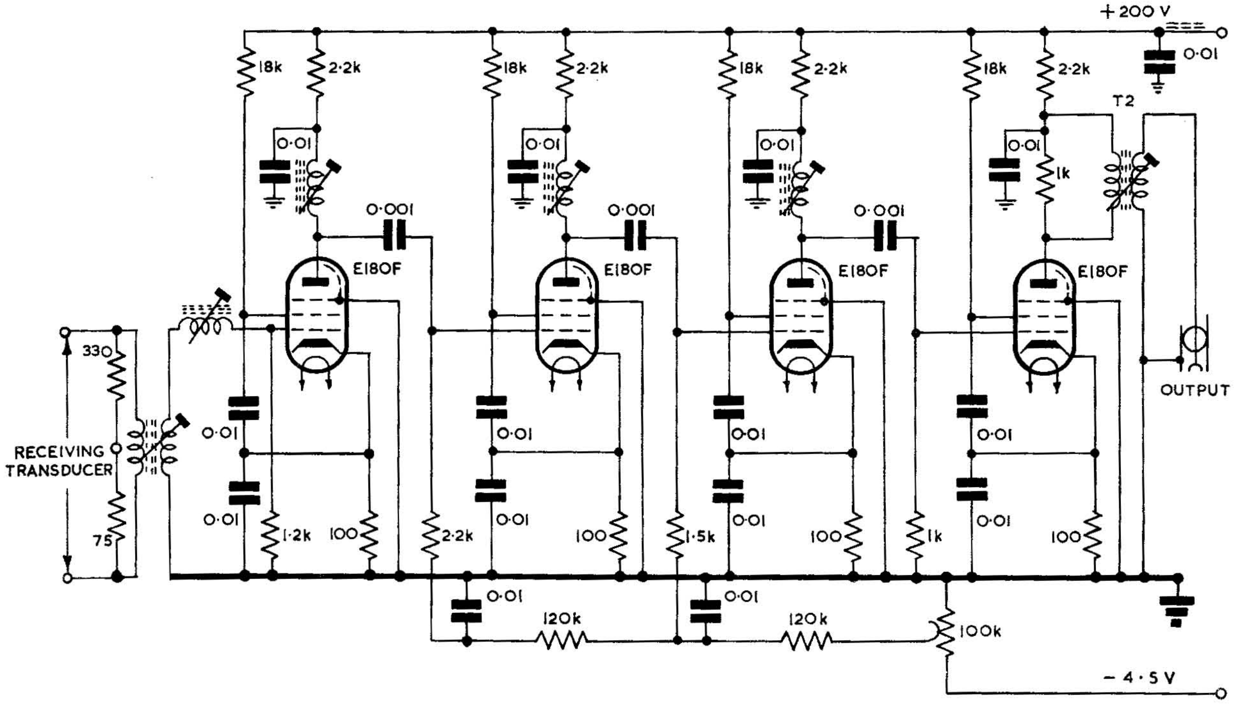

Fig. 14 - Circuit diagram of the output amplifier

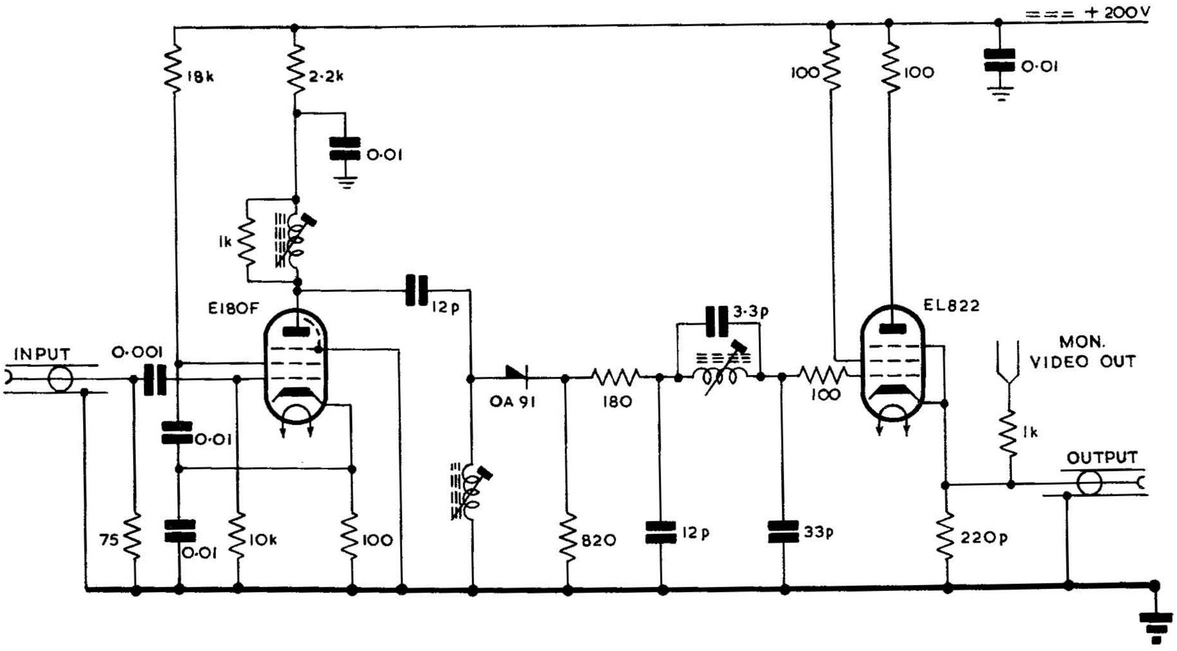

Fig. 15 - Circuit diagram of the detector and video amplifier

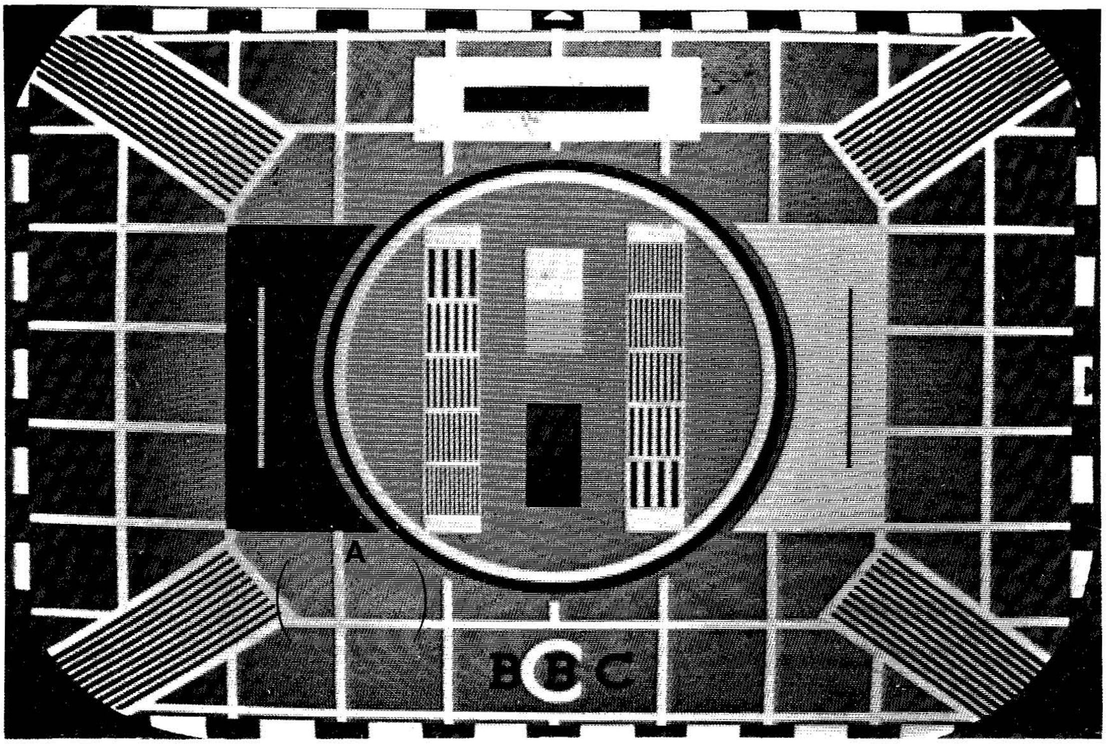

Fig. 16 - Picture input to the video delay unit

A - An example of moiré patterning due to printing process

longer be tolerated, making the introduction of a variable equalizer necessary (preferably ganged to the delay control). When using the unit with a television system locked to mains frequency, it is frequently necessary to adjust the delay in order to compensate for changes in line-scan period. An improved version of the unit would incorporate a servo-mechanism, controlled by the television line-timing pulses, moving one of the transducers so as to maintain the delay at a constant proportion of the line-scan period.

Two further defects of the mercury delay lines became apparent during the course of this investigation. In the case of the continuously-variable line, the amplitude of the internal crosstalk increased until it was only 20 dB below that of the delayed signal. After consultation with the manufacturers, it was discovered that, in the region of the transducers, the walls of the steel tank had rusted, thereby increasing the impedance of the mutual return path.

In the case of the adjustable line, the insertion loss increased to over 100 dB. This was found to be due to the fact that a small amount of the nickel-plating from the walls of the steel tank had been transferred to the crystals, thus reducing their efficiency. Both lines were returned to the manufacturers for cleaning. After this had been carried out, the lines were found to have returned substantially to normal; however, as a consequence of the cleaning process, their attenuation/frequency characteristics were found to have changed slightly. In order to compensate for these changes, slight readjustments of the equalizing networks were necessary.

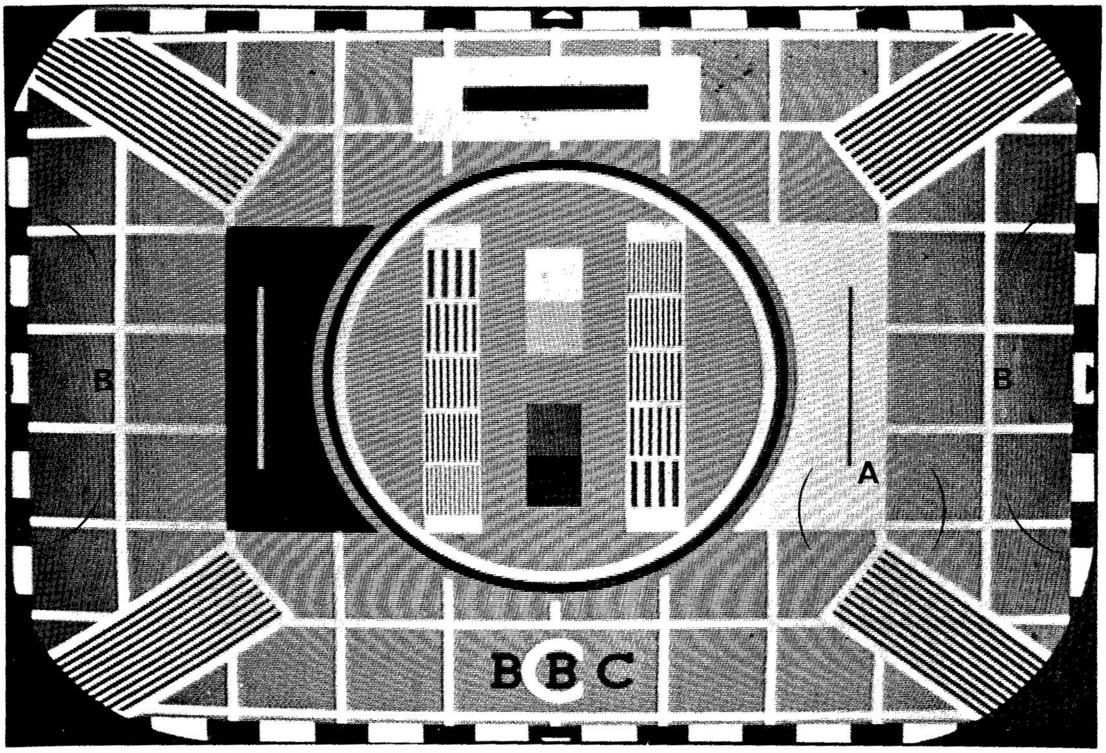

Fig. 17 - Picture output from the video delay unit after a delay of 150 μs

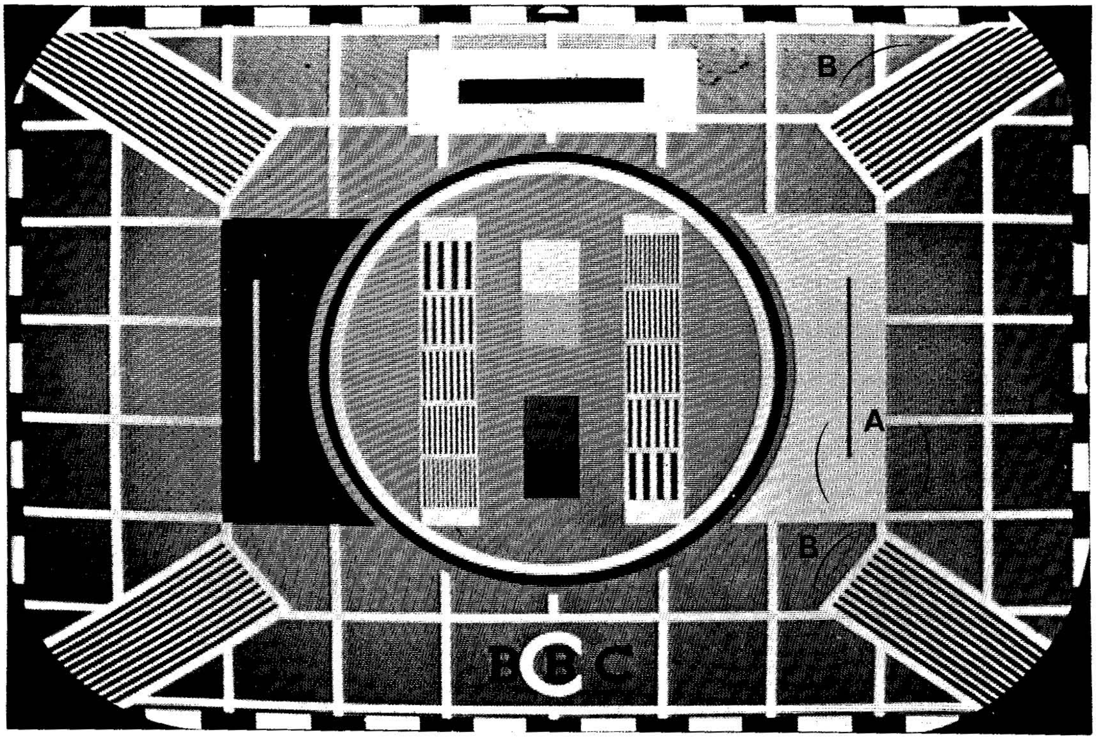

Fig. 18 - Picture output from the video delay unit after a delay of 300 μs
A – An example of moiré patterning due to printing process
B – An example of crosstalk

5. CONCLUSIONS

The mercury delay line is eminently suitable for experimental work in the field of television, for example in bandwidth-compression experiments or in the measurement of horizontal correlation data. However, before the line could be included as an integral part of operational television equipment, the problem of varying the delay of the line according to the mains frequency would have to be solved.

6. REFERENCES

1. Gander, M.C., and Mothersole, P.L., "An Aircraft Simulator for Television Signals", Electronic Engineering, pp. 408-413, July 1958.

2. Gibson, W.G., and Schroeder, A.C., "A Vertical Equalizer for Television", J.S.M.P.T.E., Vol. 69, No. 6, pp. 359-401, June 1960.

3. Chaste, R., and Cassagne, P., "The Henri de France Colour Television System", Proc.I.E.E., Vol. 107, Part B, No. 36 pp. 499-507, November 1960.

4. Brockelsby, C.F., "Ultrasonic Mercury Delay Lines", Electronic and Radio Engineer, Vol. 35, New series No. 12, pp. 446-452, December 1958.

5. Roth, W., "Piezoelectric Transducers", Proc. I.R.E., Vol. 37, No. 7, pp. 750-758, July 1949.

6. Beveridge, H.N., and Keith, W.W., "Piezoelectric Transducers for Ultrasonic Delay Lines", Proc. I.R.E., Vol. 40, No. 7, pp. 828-835, July 1952.

BIBLIOGRAPHY

Mason, W.P., "Electromechanical Transducers and Wavefilters", Second Edition New York, Van Nostrand, 1948.

Mason, W.P., "Piezoelectric Crystals and their Application to Ultrasonics", First Edition, New York, Van Nostrand, 1950.

Richards, R.K., "Digital Computer Components and Circuits", Van Nostrand, 1957.

McSkimin, H.J., "Theoretical Analysis of the Mercury Delay Line", J.A.S.A., Vol. 20, No. 4, pp. 418-424, July 1948.

APPENDIX

DESIGN OF A DETECTOR FILTER

The circuit of the filter section used in the detector is shown in Fig. 19. The attenuation function of such a network has a pole-zero configuration as shown in Fig. 20 and is of the form

$$A(p) = \frac{1 + a_1 p + a_2 p^2 + a_3 p^3}{1 + b_2 p^2} .$$

The condition for such a function to have a maximally-flat frequency response may be found by multiplying the function by $A(-p)$ and equating, as far as possible, the coefficients of equal powers of p in the numerator and denominator. Hence

$$A(p) \cdot A(-p) = \frac{1 + (2a_2 - a_1^2)p^2 + (a_2^2 - 2a_1 a_3)p^4 - a_3^2 p^6}{1 + 2b_2 p^2 + b_2^2 p^4} ,$$

and the conditions for a third-order maximally-flat response are

$$2a_2 - a_1^2 = 2b_2 \qquad (1)$$

$$a_2^2 - 2a_1 a_3 = b_2^2 \qquad (2)$$

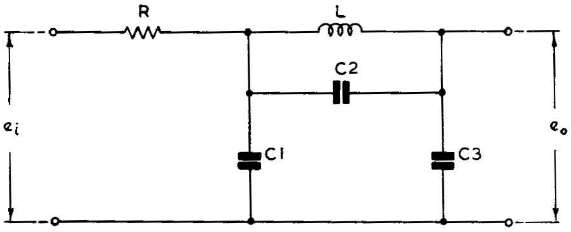

Fig. 19 - Circuit diagram of the detector filter

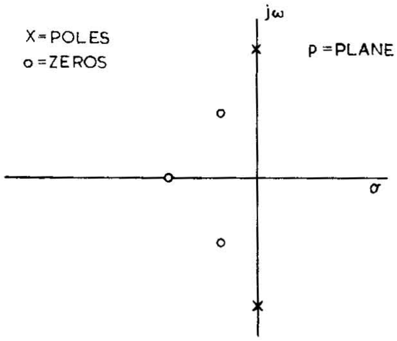

Fig. 20 - Poles and zeros of the attenuation function of the detector filter

In order to specify the performance of the network, the coefficients (a_1, a_2 etc.) may be stated in terms of a cut-off frequency (ω_0) and a parameter "m" where

$$m = \left[1 - \left(\frac{\omega_0}{\omega_\infty}\right)^2\right]^{\frac{1}{2}} ,$$

and ω_∞ is the frequency at which there is maximum attenuation. It is apparent from Fig. 20 that the frequency of maximum attenuation is the point at which the poles occur on the imaginary axis, hence

$$b_2 = \frac{1}{\omega_\infty{}^2} \qquad (3)$$

The value of the cut-off frequency may be defined as

$$\omega_0^2 = \frac{a_1}{2a_3} \qquad (4)$$

This definition of ω_0 was chosen in order to make the normalized transfer function of the network identical to that of a similar conventional "m-derived" filter section having the same values of m and ω_0.

Solving equations (1), (2), (3) and (4), for the required coefficients we obtain the expression

$$A(p) = \frac{1 + \dfrac{2m}{\omega_0} p + \dfrac{1 + m^2}{\omega_0{}^2} p^2 + \dfrac{m}{\omega_0{}^3} p^3}{1 + \dfrac{1 - m^2}{\omega_0{}^2} p^2} \qquad (5)$$

An analysis of the circuit of Fig. 19 leads to the expression

$$A(p) = \frac{1 + R(C_1 + C_3)p + L(C_2 + C_3)p^2 + RL(C_1C_2 + C_2C_3 + C_3C_1)p^3}{1 + LC_2p^2}.$$

The values of the circuit elements may now be determined by equating the coefficients of this expression to those of expression (5), and solving the equations so set up.

The solutions of these equations are tabulated in Table 1; the values of the circuit components for the conventional "m-derived" filter are included for comparison.

TABLE 1

Circuit Component	Detector Filter	"m-derived" Filter
R	R	R
C_1	$\dfrac{1}{\omega_0 R} \cdot \dfrac{2m^2 - 1}{2m}$	$\dfrac{m}{\omega_0 R}$
C_2	Chosen to resonate with L at f_∞	
C_3	$\dfrac{1}{\omega_0 R} \cdot \dfrac{2m^2 + 1}{2m}$	$\dfrac{m}{\omega_0 R}$
L	$\dfrac{R}{\omega_0} \cdot \dfrac{4m^3}{2m^2 + 1}$	$2m \dfrac{R}{\omega_0}$
Terminating Resistor	∞	R

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